A SIMULATION-BASED CONCEPT FOR ASSESSING THE EFFECTIVENESS OF FORGIVING ROADSIDE TREATMENTS

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ABSTRACT

To increase road safety, the concept of forgiving roadsides is one of the main priorities in the area of road infrastructure measures. It mainly aims to mitigate the consequences of single vehicle accidents—and especially run-off-road accidents—, which are responsible for nearly half of all road accident fatalities in the European Union. This paper introduces a novel approach for analyzing the necessity and effectiveness of forgiving roadside treatments. The work comprises simulations of various run-off-road accident scenarios at real accident black spots as well as the analysis of vehicle dynamics. The proposed concept is based on an accurate replication of real road sections by creating a three-dimensional road model. In simulation, various roadside designs with either single fixed roadside objects or continuous objects such as safety barriers are implemented to obtain information about their effect on safety. Indicators for the effectiveness of roadside treatments are the head injury criterion (HIC) and the abbreviated injury scale (AIS), which describe the injuries to occupants involved in collisions. Simulations show that the risk of fatal injuries strongly declines with forgiving roadside design. In future, the concept could be utilized for road safety inspections and road safety audits in order to assess safety levels.

Keywords: Road accident, forgiving roadside, simulation, HIC, AIS

INTRODUCTION

In the year 2001, the European Commission announced the “White paper on Transport Policy”, which aimed to reduce the number of road accident fatalities by 50 percent until 2010. Looking at road accident statistics for the year 2009, a reduction of about 36 percent with 34,500 fatalities could be observed (European Commission 2010). However, to further decrease this number, various developments in the field of road safety are necessary. Especially single vehicle accidents (SVA) have a high reduction potential, since they account for about 45 percent of all fatal accidents (RISER Consortium 2006). For SVAs, one can distinguish between on-road accidents and run-off-road accidents (RORA), where vehicles leave the road without interfering with other vehicles. An approach to reduce the severity of RORAs are forgiving roadsides, which aim to ensure that errant vehicles regain control, or at least mitigate the consequences of collisions with roadside obstacles. The roadside is defined as the area beyond the carriageway and mostly includes elements such as slopes, ditches and various obstacles (e.g. trees, utility poles or masonry structures). Strategies for forgiving roadsides have already been stated by the Federal Highway Administration (1986), AASHTO (2002) or in numerous national guidelines. A high number of studies and research works were carried out to determine the impact of various roadside features on frequency and severity of accidents (cf. Holdridge et al. 2005; Lee & Mannering 2002; Ray 1999; Stamatiadis & Pigman 2009). A study by Nitsche et al. (2010) summarizes state-of-the-art treatments to make roadsides forgiving, as well as harmonizes currently applied standards and guidelines. Accordingly, the following three groups of treatments can be applied:

1. Remove or relocate obstacles on the roadside to provide clear zones
2. Modify obstacles to make them break-away or crashworthy
3. Shield obstacles by installing road restraint systems (RRS)

Assessing the effectiveness of different roadside treatments in terms of safety requires either before/after analyses of accident data or cost-intensive full-scale tests of specific installations (Sicking 2001). The usage of simulation-based assessment methods reduces costs and allows studying the implications of pre-defined interactions. For assessing performances of road restraint systems, nonlinear Finite-Element (FE) simulation software such as DYNA3D can be applied. It provides accurate information about a vehicle-object collision, as used in crash-tests, e.g. in the new car assessment program (EURO-NCAP 2011). The European Norm EN 1317 describes requirements for RRS and corresponding testing criteria so that simulations can be validated with real crash tests (Rens 2009).

For the investigation of accident circumstances, accident reconstruction tools such as PC-Crash, CarSim, EDCRASH, AnalyserPro or HumanVehicle Environment can be used. With this software, the accident related factors can be identified. This is typically done by backwards simulation, starting with the end positions of the vehicles. On the other hand, forward simulations of accidents can be carried out to create fictional scenarios and to analyze the dynamic behavior of the vehicle. This paper deals with such a concept and describes how to assess the effects of roadside treatments on safety. To do this, a framework has been created, which comprises the development of three independent types of models, namely the road, the vehicle and the driver. The key issue of this framework is the three-dimensional road model, which is created from laser measurements of a mobile high-tech laboratory. In simulation, several scenarios of RORAs with different roadside treatments are generated to analyze vehicle dynamics and the impact on occupant injury severity.

This paper describes the concept developed and is structured into five main sections. The first section presents the modeling and simulation framework, which is applied to simulate RORA scenarios. Subsequently, the methodology for assessing the effectiveness based on simulation results is described. The third section discusses the calibration and validation of simulation models. The fourth section deals with preliminary assessment results, before the paper is concluded with the main findings and future work.

SIMULATION FRAMEWORK

The simulation framework presented in this paper is utilized as a tool to assess the effects of road parameters on vehicle behavior and roadside safety. For this work, PC-Crash is used as simulation software. Its object and collision models are validated and tested for more than 15 years as published in several papers (cf. William 1996). Road parameters such as road alignment, surface roughness or skid resistance are integrated from real road sections using measurement data of the Austrian road network. By using the road parameters of high risk accident sites, it is possible to reconstruct the accidents and directly incorporate roadside treatments in simulation. The framework is illustrated in Figure 1.

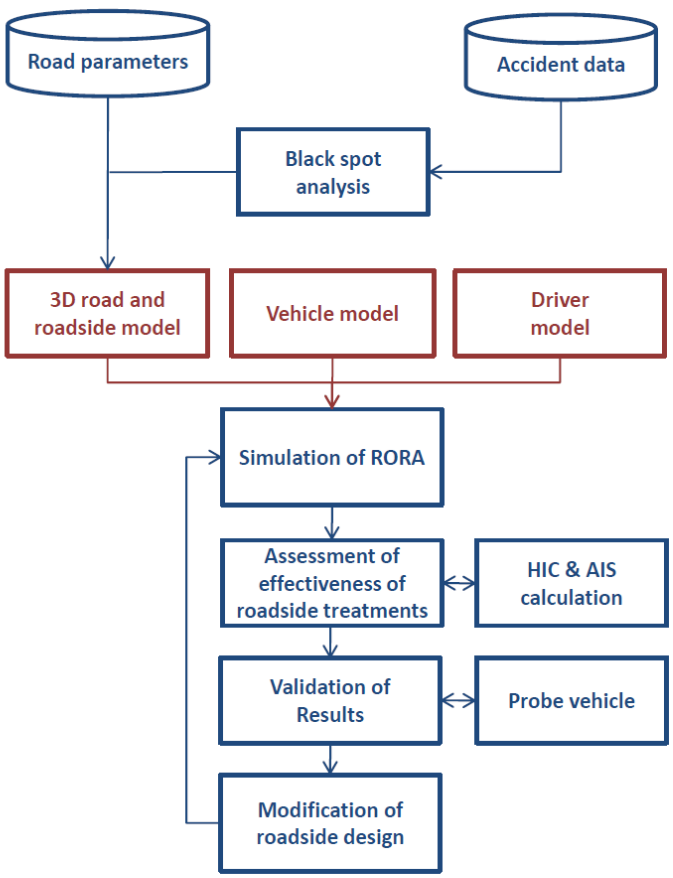

Figure 1: Simulation framework

In Austria, every road accident with at least one person injured is recorded by the police. A database of all Austrian road accidents with person damage from the year 1994 to 2010 is used for this work. It includes information about the involved people, vehicles as well as the location and accident circumstances. Accident data are then used to identify high risk sites, further denoted as accident black spots, according to the Austrian guidelines for road construction. An accident black spot is defined as a location with a maximal range of 250 meters, where within three years five accidents or at least three similar accidents (e.g. SVAs) happened (FSV 2004).

In this research work, the black spots identified are reconstructed in a virtual environment by using a three-dimensional road model, which is calculated from road parameters measured by a mobile laboratory called RoadSTAR. Together with a vehicle and a driver model, the obtained road model is the basis for the simulations, where various roadside safety treatments are implemented. For each safety treatment, vehicle dynamics as well as occupant injury severities are evaluated to assess its effects on safety. In future work, simulation results are validated by using a probe vehicle to perform specific maneuvers on a test track.

Black spot analysis

Based on accident data of the Austrian road network, black spots are identified in order to reconstruct them in the simulation framework. To acquire the most relevant black spots, accident data is filtered as follows. It is reasonable to restrict the timeframe to the last five years (2005 to 2009), since it can be assumed that older black spots have already been investigated by the respective road administration. Secondly, the vehicle type is limited to passenger cars only, because they account for the majority of all accidents and are the determinant factor for road design. Moreover, this paper focuses only on rural roads, because RORAs are less frequent in urban areas. The simple reason is that collisions with parking vehicles or pedestrians are handled in separate accident types and the requirements for roadside design differ in urban areas. As another constraint, only bends are observed, where RORAs are considered more likely than on straight road sections.

This query results in a total number of 6,700 RORAs. The distribution of accident types shows that nearly all RORAs in bends can be assigned as SVA. Only in a few cases (less than three percent), an oncoming vehicle was reported as accident-relevant. Therefore, they have been excluded from further investigations. The remaining RORAs show that two thirds of all accidents happened on the outside of the bend. For these accidents, left bends are more frequent than right bends. Accidents on the outside of a right bend are less likely, since vehicles have to pass the opposing traffic lane, which causes two possible scenarios. On the one hand, the opposing traffic lane is free of oncoming vehicles, so that errant vehicles have additional time and space to regain control and can avoid the accident. On the other hand, collisions with oncoming vehicles occur, which are not part of the conducted accident survey.

Further investigations concerning the accident severity were performed. It was found that nearly three percent of all RORAs ended fatally, 15 percent had severe consequences and for 15 percent the injury severity was not determinable on the spot[1]. The evaluation of RORAs in combination with fixed object collisions recorded (such as trees) showed an increasing fatality rate of more than 10 percent. This is equivalent to nearly one-third of all RORA fatalities observed and indicates that safety treatments are necessary. Hazardous accident locations in Austria are

[1] In the Austrian road construction guidelines, not determinable accidents are allocated as severe accidents in 90 percent of all cases.

identified with respect to the criteria described above. To determine the most hazardous black spots in the Austrian road network, the results were ranked according to accident frequency and more importantly their severity. For this purpose, the average accident severity U_m is used, which is given in Equation 1.

$$U_m = \frac{u_l \cdot p_l + u_m \cdot p_m + u_s \cdot p_s}{\text{Amount of all accidents}} \tag{1}$$

where:
u_l: Amount of slight accidents
p_l: Weighting factor for slight accidents = 5
u_m: Amount of severe accidents
p_m: Weighting factor for severe accidents = 70
u_s: Amount of fatal accidents
p_s: Weighting factor for fatal accidents = 130

The weighting factors are determined using the accident costs of each degree (FSV 2004). With this quantity, a statement about the injury risk at specific spots can be given.

Road and roadside models

The road models used for this simulation framework are representations of specific road sections in Austria. All Austrian high-level road networks are periodically monitored using the mobile laboratory RoadSTAR. It measures numerous road surface and geometry parameters such as skid resistance, transverse and longitudinal evenness, texture, gradient and course angle, while driving at a speed between 40 and 120 km/h. Moreover, it captures stereo video data and allows precise measurements of road features such as lane width or traffic signs. In combination with a differential GPS unit and an inertial measurement unit (IMU), these parameters can be referenced to their position. Figure 2 illustrates the RoadSTAR system and its sensor equipment (Maurer et al. 2002).

Figure 2: RoadSTAR system (Maurer et al. 2002)

For the measurement of the skid resistance, a modified Stuttgart skiddometer is used (cf. Opitz 2005). Texture and evenness are measured by using laser scanning systems, while the road geometry parameters are derived from the IMU. Crack detection is handled by an image processing system. The road parameters of the accident black spots identified before are used to generate road models. The parameters necessary to build a three-dimensional road model from measurements are listed in Table 1.

Table 1: Road parameters necessary for road models

Parameter	***Description***	***Resolution***
Skid resistance μ [-]	skid resistance measurements of pavements	5 m
Gradient s [%]	slope of the road surface	1 m
Crossfall q [%]	crossfall of the road surface	1 m
Heading angle ϕ [deg]	derived from IMU	1 m

The transverse and longitudinal evenness are averaged for one meter and represent the lateral and longitudinal profile of the road. The angle of gradient ψ_i (in radians) for each measurement is given by

$$\psi_i = \operatorname{atan}(s_i/100), \tag{2}$$

where $i \in \{0, \dots, n-1\}$ and n denotes the number of measurement records.

When using ψ_i together with measurements for the heading angle ϕ_i, these two quantities allow for the calculation of the road centerline. The three-dimensional coordinates of the centerline can be recursively generated as follows:

$$x_i = x_{i-1} + \psi_i \cdot \cos(\phi_i) \cdot \frac{\pi}{180} \tag{3}$$

$$y_i = y_{i-1} - \psi_i \cdot \sin(\phi_i) \cdot \frac{\pi}{180} \tag{4}$$

$$z_i = z_{i-1} + \sin(\psi_i) \tag{5}$$

where $i \in \{1, \dots, n-1\}$.

Initial values for the recursion are given by the origin $(0, 0, 0)$ of the reference coordinate system. For a proper visualization of the road model, positive height values are required. Therefore, the z-coordinates are adjusted by

$$z_i = z_i + z_{\text{offset}}, \qquad i \in \{0, \dots, n-1\}, \tag{6}$$

where $z_{\text{offset}} = \min(z_i)$.

At every point of the road centerline, lateral profiles with crossfall $q_i, i \in \{0, \dots, n-1\}$ are added to the road model. These profiles are perpendicular to the tangent vector of the centerline and determine the surface of roadway.

In a last step, friction polygons with a sampling interval of five meters are generated out of the skid resistance data. For this purpose, the endpoints of the corresponding lateral profiles are projected to the *x*-*y* plane by setting the *z*-coordinates to zero. Subsequently, these points are triangulated (see Figure 3) and stored as 3DFACES in a DXF file (Drawing Exchange Format), which can easily be imported into PC-Crash.

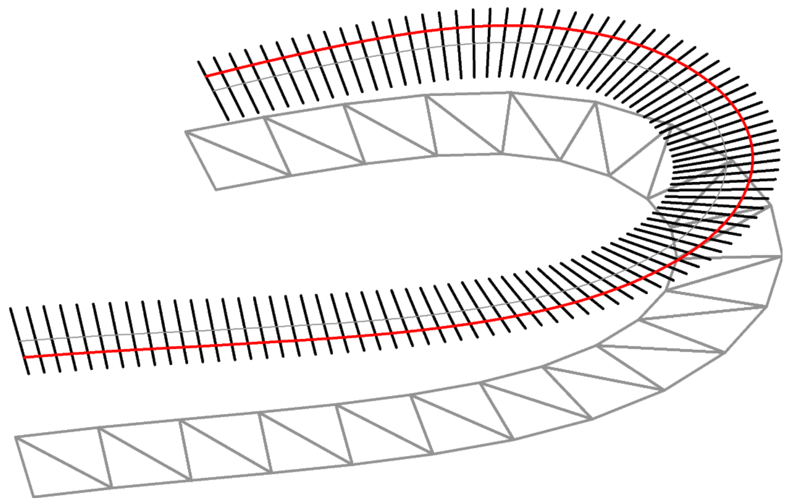

Figure 3: Representation of a two-lane road model (red: RoadSTAR trajectory; black: lateral profiles; gray: friction polygons)

According to Maurer (2007), the friction coefficient has an influence on the vehicle behavior on wet or dirty road surfaces and can be classified into five categories (cf. FSV 2006):

Class 1: $\mu > 0.75$
Class 2: $0.59 < \mu \leq 0.75$
Class 3: $0.45 < \mu \leq 0.59$
Class 4: $0.38 < \mu \leq 0.45$
Class 5: $\mu \leq 0.38$

For the implementation of forgiving roadside treatments, it is necessary to enhance the 3D road model. The slope-profile function enables the modification of a 10 meters wide area along the road. This allows the modeling of clear zones, side-slopes (declining) and cut-slopes (inclining). The slope can be assigned with absolute distance values, degrees or percentages and remains constant for the whole road section. For the implementation of hard shoulders, the road width is increased to model a paved area, while for soft shoulders the slope-profile is used to model the nearest part to the road as flat gravel area. The distinction between the shoulder types is made by drawing different friction polygons. Original measurement data of skid resistance on shoulders are not available, but it can be assumed that a hard shoulder has a wet friction value of 0.45 to 0.6 (class 3) and a soft shoulder 0.2 to 0.38 (class 5). The grass area, on the other hand, has a wet friction value of only 0.1. In future, the RoadSTAR will be additionally equipped with a 3D laser scanning system, which records the roadside objects and geometry. With this information, the roadside will also be generated out of real measurement data to enable nearly complete images of the road and roadside.

Vehicle and object models

The software PC-Crash comprises a database with a high number of different vehicles types (passenger cars, trucks, motorcycles, bicycles etc.) and brands. For this paper, a BMW X3 model is used as the vehicle for RORA simulations. Objects such as trees, poles or RRS are also handled as vehicle models, but differ in shape, weight or elasticity. For vehicles and objects, the following settings are essential (Dr. Steffan Datentechnik 2001 & 2009):

- *Vehicle geometry*: This is the basic information, which can be loaded from the database or entered manually. It determines the dimensions and weight of the vehicle. Additionally, the anti-lock braking system can be enabled in this field. All other parameters are calculated with respect to these inputs.
- *Suspension properties*: The suspension properties determine the behavior of springs and dampers, as well as the likelihood for rollovers. The calculation is based on the static load on each wheel. Three different suspension settings can be selected, namely normal, stiff or soft.
- *Occupants & cargo*: These properties define the additional mass of occupants and cargo.
- *Rear brake force*: The rear brake force describes the braking characteristic of the rear brake in dependency of the geometry and suspension properties,
- *Vehicle shape*: The vehicle shape defines the optical illustration of the vehicle. It can be assigned by vehicle body dimensions, or by importing a suitable DXF-file.
- *Trailers*: These properties define the trailer characteristics. It covers the type (steered, unsteered), geometry properties (drawbar length etc.) and forces at the joints.
- *Stability parameters*: The stability parameters deal with the behavior of the Electronic Stability Control (ESC). Typical properties are the time and the activation threshold.

As an additional step, the impact parameters of the vehicle are defined. The impact is calculated according to a momentum-based impact model described by Tomasch (2004), which is resolved in an infinitely small timeframe at a single impact point. Amongst several parameters for the collision, a crucial one is the *k*-factor, which is defined as the quotient of the restitution phase *R* and the compression phase *C*:

$$k = \frac{\mathrm{R}}{\mathrm{C}} \tag{7}$$

A ratio of *k*=1 determines an ideal elastic impact, while a ratio of *k*=0 is a plastic impact. Typically, a collision is semi-elastic with a ratio of 0.1. Other parameters are the contact plane and the friction coefficient at the impact point. These two parameters define the sliding characteristics in the impact area. The contact plane is fixed to be normal to the vehicle and the sliding is reached with a value of 0.3.

Another important characteristic of the vehicle is the tire model. For the simulations, the TMeasy tire model is used, which enables non-linear effects (Hirschberg et al. 2007; Brach 2008). Besides the dimensions or diameter of the tires, longitudinal and lateral characteristics can be applied separately according to the tire force characteristic curves, where the following properties are used for both:

- The peak frictional force value F_{max}=1.1
- The slip value, at which F_{max} appears s_{max}=0.21
- The sliding frictional force F_{slip}=1
- The slip value at which F_{slip} appears s_{slip}=0.5
- The slope of the tire model curve at the origin F_{0p}=15

Moreover, the proposed simulation framework allows incorporating road restraint systems such as guardrails. Thus, the effectiveness of guardrails in comparison to a non-shielded roadside can be evaluated. For the implementation of RRS, several single elements (single object models) are connected as trailers. Standard models for delta blocks and guardrails exist, which can be used in the simulation. As described above, properties such as mass, geometry and forces can be adopted individually. Tomasch et al. (2011) carried out a study to determine the optimal length of guardrails before roadside hazards. Accordingly, the length of the guardrail is related to the speed at which vehicles run off the road. This relationship function is the basis for guardrail lengths in the object models of this work. Important for the implementation of the RRS is the anchoring of the system into the ground. For this purpose, the first and last elements are assigned with a higher mass and their center of gravity (CoG) is defined at the bottom.

For the calculation of the vehicle dynamics, a kinetic model is used, which calculates the forces with respect to the following rules:

1. Lateral and longitudinal tire forces are defined by the lateral slip angle and deceleration or acceleration force.
2. Accelerations in the center of gravity and rotational accelerations are calculated based on external forces, which are defined in the local, vehicle-related, coordinate system.
3. Accelerations are afterwards transformed from the local to a global coordinate system.
4. Equations of motion are numerically solved over a defined time step of typically 5 ms.
5. Velocity change and the updated position of the CoG are calculated.
6. Based on suspension parameters, the wheel load of each tire is calculated.

Driver models

For most accident reconstruction tasks, it is practical to use backwards simulation, since end position and skid marks are known. For the purpose of this research, forward simulation is used, so that vehicles have a defined starting position and drive along a specified path. Driving maneuvers are sequentially performed. This means that the driver executes manual inputs systematically, while the type, time/distance and property of the maneuver can be defined in each sequence. The typical sequences are braking, accelerating and reacting. For braking/accelerating sequences, additional steering inputs can be assigned. However, they are typically realized by defining a vehicle path, where the kinetic path driver model calculates the necessary steering angle according to the current linear and angular vehicle position with respect to the next appearing path point. This path point is dependent on the look-ahead distance, which is velocity dependent (see Figure 4, Equations 8–12), while the acceleration and braking sequence is not affected by the path driver model.

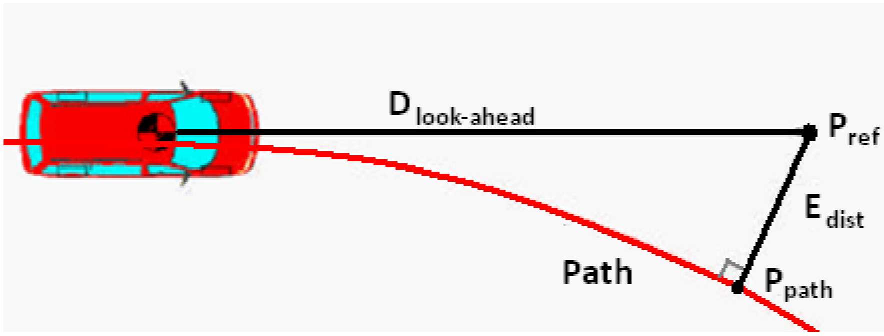

Figure 4: Look-ahead distance (Dr. Steffan Datentechnik 2001)

$$P_{ref} = P_{vehicle} + D_{look-ahead} \cdot \vec{d}_{vehicle} \tag{8}$$

$$D_{look-ahead} = T_{look-ahead} \cdot v_{vehicle} \tag{9}$$

$$E_{dist} = \left(P_{ref} - P_{path}\right) \cdot \vec{n}_{path} \tag{10}$$

$$E_{angular} = \theta_{vehicle} - \varphi_{path} \tag{11}$$

$$\vec{n}_{path} = \begin{pmatrix} -\sin(\varphi_{path}) \\ \cos(\varphi_{path}) \end{pmatrix} \tag{12}$$

where:

P_{ref}:	Reference point for the calculation of the displacement
$P_{vehicle}$:	Reference point of the vehicle position (commonly the CoG)
$v_{vehicle}$:	Vehicle velocity
$D_{look-ahead}$:	Look-ahead distance
$T_{look-ahead}$:	Look-ahead time
$\vec{d}_{vehicle}$:	Vehicle direction vector (heading)
E_{dist}:	Linear displacement
$E_{angular}$:	Angular displacement
P_{path}:	Next appearing path point
$\vec{n}_{path}$:	Normal vector on the path at point P_{path}
φ_{path}:	Direction of the path at point P_{path}

For a cornering maneuver with constant velocity, this means that the steering angle is adjusted according to the next path point, while the velocity is only affected by the occurring vehicle dynamics. If physical limits are exceeded, the vehicle will start to slide or roll over. The path driver does not react on this event with typical human behavior (e.g. counter steering, braking), but still tries to reach the next path point. The vehicle path can be adjusted manually by moving, inserting and deleting path points. The standard driving line is in the center of the lane and is equivalent to an 'ideal maneuver'. In reality, especially when looking at curves, the actual trajectories of vehicles differ quite often. According to a study by Spatzek (1999), six different driving maneuvers can be observed in curves, which are illustrated in Figure 5.

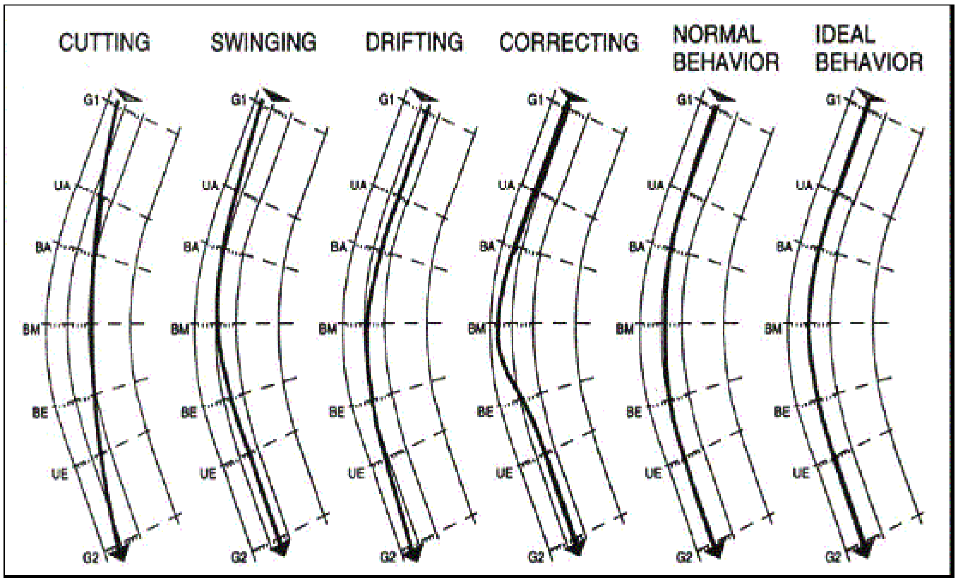

Figure 5: Driving behavior in bends (Spatzek 1999)

The purpose of the study was to assess the relation between driving maneuvers and accident risk in bends. Driving maneuvers at seven curves with different radii and sight distances were recorded. It was found that about one third of all drivers did not use the normal or ideal driving line. Especially the cutting of the curve was a frequently observed maneuver. Real accident black spots are reconstructed for the simulation scenarios of this paper. However, information about the actual driving maneuver and driving velocity are not available from accident data. Inspections at the spot have to be performed by the police or accident assessors in order to identify indicators such as skid marks. For this reason, the ideal trajectory is used as an initial condition and manual reaction and correction sequences are not performed.

Occupant models

For simulation-based reconstruction of traffic accidents, the vehicle-vehicle or vehicle-obstacle interaction is of considerable importance in order to gain knowledge about the accident circumstances. If interactions with occupants or pedestrians must be observed, additional simulation features are needed. The most common approach is a multi-body system, which connects several individual bodies to one entity using pivoting joints. A typical occupant in PC-Crash is modeled out of 20 different bodies (torso, hip, neck, head etc.) and 19 joints. Each body has different properties such as geometry, mass, stiffness or friction coefficient. Additionally, elements such as the seat or seatbelt can be modeled with the multi-body system. By using this feature, statements about the body forces and accelerations can be made, which is necessary to assess the injury severity related to a crash (Steffan 2000).

ASSESSMENT METHODS

A correlation between vehicle dynamics and occupant injuries is estimated for the assessment of effectiveness of roadside treatments. For this purpose, different methods can be applied. One approach is the delta-v calculation, which takes the difference between the velocity before and after a collision. However, the usage of multi-body models enables more sophisticated assessment methods. Since the head is one of the main affected regions of car accidents, the head injury criterion is a suitable method. Statements about the possible injury severity can be given in combination with a classification according to the abbreviated injury scale (AIS).

Head Injury Criterion (HIC)

The head injury criterion is defined as the acceleration a acting on the head during a crash. In literature, two different time frames for HIC are used. According to a study by Eppinger (2000), the former 36 ms used are replaced by 15 ms, which are typically notated as HIC_{36} and HIC_{15}:

$$\text{HIC}_{15} = (t_2 - t_1)\left\{\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a(t)\,dt\right\}^{2.5} \tag{13}$$

where:
t_1: start of crash pulse
t_2: end of crash pulse

The relationship between HIC and injury is an important topic, which can be found in several highway and airline safety standards. It is one of the main criteria in the New Car Assessment Program and the Federal Motor Vehicle Safety Standard 208 and 213 (Hutchinson 1998).

Abbreviated Injury Scale (AIS)

The abbreviated injury scale is an indicator for accident severity in the head and neck region. It separates the injury severity into different categories (Burg 2007; Edl 2010), whereas no injury is denoted as level 0 and unknown injury as level 9:

- AIS 1 (Minor injury): light injuries such as headache, with no loss of consciousness and no long hospital stay
- AIS 2 (Moderate injury): up to 15 minutes loss of consciousness, face or nose fractures
- AIS 3 (Serious injury): more than 15 minutes loss of consciousness without severe neurological damage
- AIS 4 (Severe injury): skull fractures with severe neurological damage
- AIS 5 (Critical injury): up to 12 hours loss of consciousness, critical neurological indicators
- AIS 6 (Fatal): death

Many studies were carried out to link measurements from HIC to AIS. Mertz et al. (1997) published their work on the injury risk curves for children and adults in front and rear collisions. These curves were later adapted by the National Highway Traffic Safety Administration (NHTSA 1999). They published an expanded Mertz/Prasad curve, which states the chance of specific AIS levels in relation to the HIC up to a value of 3000. Based on these data, the following curves can be reproduced (see Figure 6).

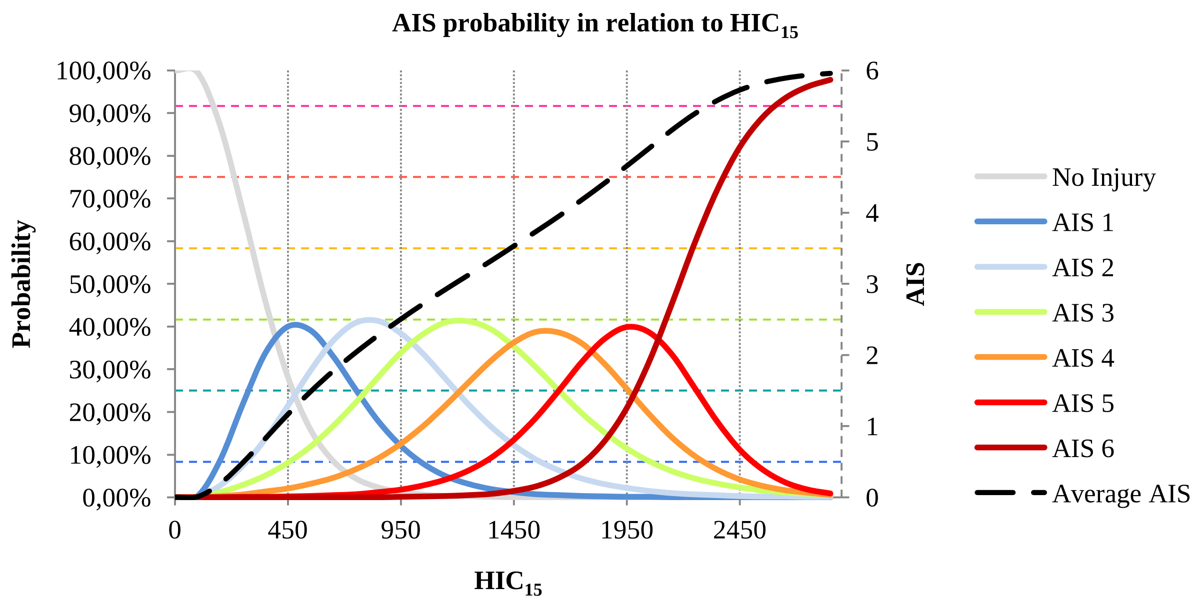

Figure 6: AIS probability in relation to HIC_{15}

Each of the curve states the probability of a specific AIS level in relation to the HIC value and the dashed line represents the average AIS value. Consequently, every HIC value can be related to a corresponding AIS level. For example, at HIC_{15}=450, a probability of 28 percent for no injury, 40 percent for AIS 1, 21 percent for AIS 2 and about 10 percent for AIS greater than 3 are expected. This gives an average AIS level of 1.17. Since AIS is commonly classified into integer values, the corresponding AIS level is rounded to 1. Serious injuries are expected starting with an AIS level greater than 2 or an HIC of about 1000. This is the limit for most of the crash tests to be fulfilled. The relation between HIC and AIS is summarized in Table 2:

Table 2: Relation between AIS level and HIC

HIC	*AIS level*
0–250	0
251–550	1
551–949	2
950–1449	3
1450–1899	4
1900–2299	5
>= 2300	6

MODEL CALIBRATION AND VALIDATION

In order to utilize the proposed simulation framework as an effective tool for accident research, the results have to match reality. Consequently, accurate simulation models need to be calibrated and validated. For this simulation framework, calibration comprises several types of model adjustments. The parameters of the vehicle models such as suspension or stability parameters must be adjusted in order to match with characteristics of the certain simulation scenario. For example, if the consequences of a RORA with a heavy-weight-vehicle are of interest, then the vehicle model needs to be calibrated properly. All parameters for the vehicle model calibration are listed in the model description above. The object models (on the roadside) are calibrated by adjusting parameters such as dimensions, elasticity or mass. These settings have a strong influence on impact severity in case of a collision. In this work, the calibration of road models is equivalent to the process of developing them based on RoadSTAR measurement data. The friction can be adjusted to differentiate between shoulders or travel lanes.

Validation is used to verify the calibrated models. PC-Crash has been validated through numerous studies and is widely accepted in the forensic community (Franck & Franck 2010). For the calculation of collisions and impacts, the validated momentum-based impact model of PC-Crash is applied (William 1996). The outputs of the large amount of different models used are subject to a validation process that is planned in future work. It is an essential component of the simulation framework, as depicted in Figure 1. A probe vehicle of AIT equipped with accelerometers and several other sensors will be used to carry out validation measurements of run-off-incidents on specific test sites. These incidents will not include object collisions, but allow a comparison of vehicle dynamics measured and simulated as well as vehicle model updating.

PRELIMINARY RESULTS OF SPECIFIC SIMULATION SCENARIOS

The simulation framework described in the previous chapters was applied to an accident black spot in Austria. At this spot, three fatal RORAs happened in the past five years, indicating that the roadside design is insufficient. In two of the three cases, a collision with an obstacle was recorded. Visual inspection of the site shows that the curve is surrounded by trees and a declining slope. It is a right bend with an angle of 180 degrees, a length of 40 meters and a radius of 12 meters, which consists of a two-way carriageway with one lane per direction (cf. Figure 7).

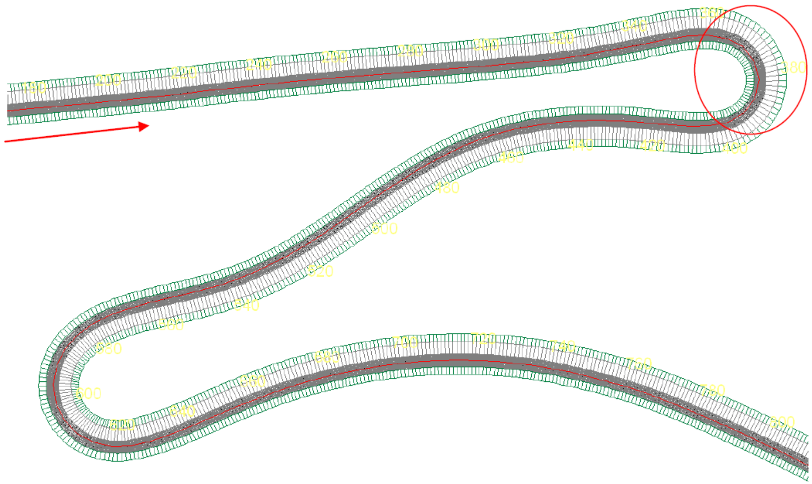

Figure 7: Road model of the accident black spot selected

All accidents occurred at the outside of the bend. For the simulation of the RORAs, the original scene has been simplified by removing the surrounding trees. In total, six scenarios with varying roadside treatments are simulated in order to evaluate their effectiveness (see Figure 8):

1. Slope: The initial scenario illustrates the curve without any forgiving roadside treatments. It consists of the two-way carriageway with a slope beyond. The slope is set to decline with 26.7 degree or 50 percent over a width of six meter. At the end of the slope, the ground is flat for another four meters. This slope profile is used for all subsequent scenarios.

2. Soft shoulder: In scenario 2, the carriageway is extended by a soft shoulder with a length of 1 meter. It is commonly a short, flat, gravel area and the wet friction value is set to μ=0.3.

3. Hard shoulder: A hard shoulder is an extension of the carriageway, although vehicles are not allowed to drive permanently on this area. It is a paved area, which is used as breakdown lane. The wet friction value is assigned with μ=0.5.

4. Safety barrier: The safety barrier is an example of RRS. In this case, a semi-rigid steel barrier is modeled, which absorbs some of the impact energy of the errant vehicle and redirects it back onto the road.

5. Clear zone: Scenario 5 illustrates a clear zone, which is free of obstacles and has no inclination or declination. This ensures that errant vehicles have time and space to regain control and can continue their trip.

6. Tree collision: In this scenario, a collision with a tree is simulated. For this reason, a single tree is placed in the vehicle sliding path of the clear zone scenario. The aim is to analyze the vehicle-tree collision without any external influences.

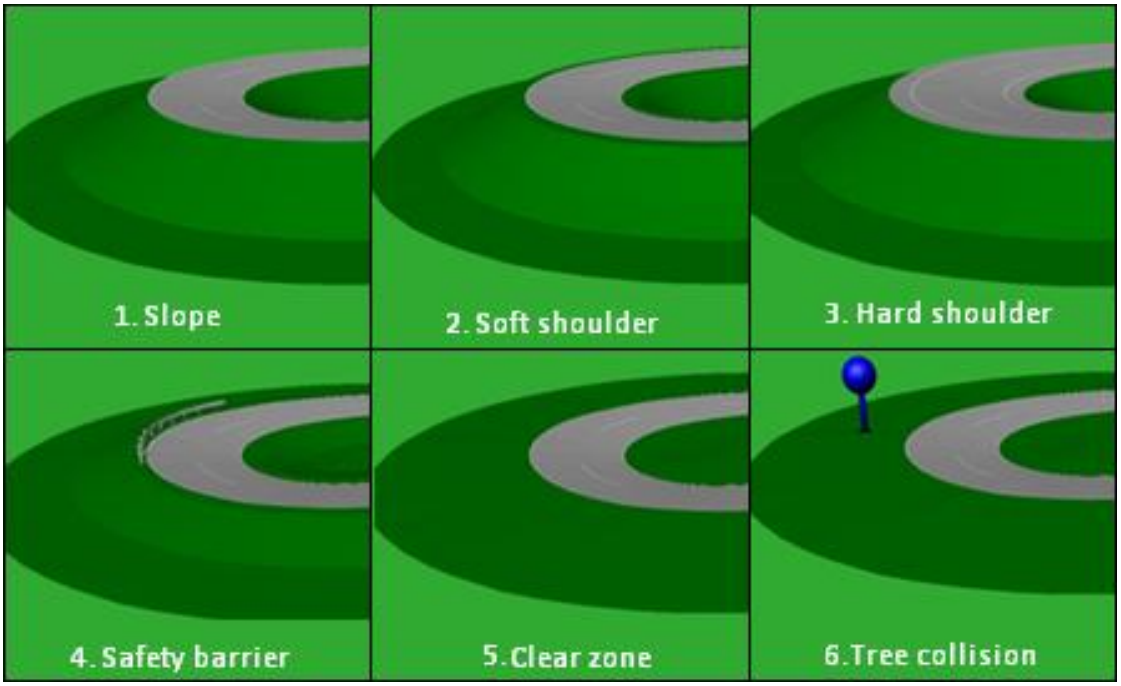

Figure 8: Simulation scenarios for forgiving roadside measures

In a first step of the simulation, the vehicle speed is continuously increased in order to identify the critical speed in the curve. It must be noted that Electronic Stability Control has been disabled for the vehicle model of these simulation runs. At 55 km per hour, the vehicle is forced to run off the road. This is the speed taken for all simulation scenarios. The vehicle movements have been analyzed for each of the scenarios separately. In the first scenario, the vehicle enters the slope and is not able to regain control. The vehicle is forced to drive along the slope and crashes into the following ground. A rollover could not be observed, but the impact was life-threatening with a HIC value of about 2,888 and AIS 6. For the soft shoulder scenario, no measurable effects could be observed. The vehicle is still running off the road and crashes into the ground with a similar HIC value and again AIS 6. On the other hand, the hard shoulder prevents the vehicle from running off the road. The vehicle gets back on the road after sliding, but with an HIC of lower than 10, no injuries have to be expected. It should be mentioned that the vehicle is still passing the opposing traffic lane, which is in fact dangerous, but this case has to be handled separately. In scenario 4, the effectiveness of the safety barrier is evaluated. The vehicle crashes into the barrier at an angle of 20 degrees. The barrier absorbs some of the impact energy so that the vehicle is able to regain control and continues its trip. The maximum HIC measured is 470, which indicates a slight injury risk with AIS 1. In the clear zone scenario, the vehicle can resume its driving maneuver without any occupant injuries. In scenario 6, a tree collision was reconstructed by placing a tree within the clear zone and in the sliding path of the vehicle. The frontal impact results in extremely high accelerations with a maximum HIC value of over 10,000 and a fatal accident. All six simulation scenarios are illustrated in Figure 9.

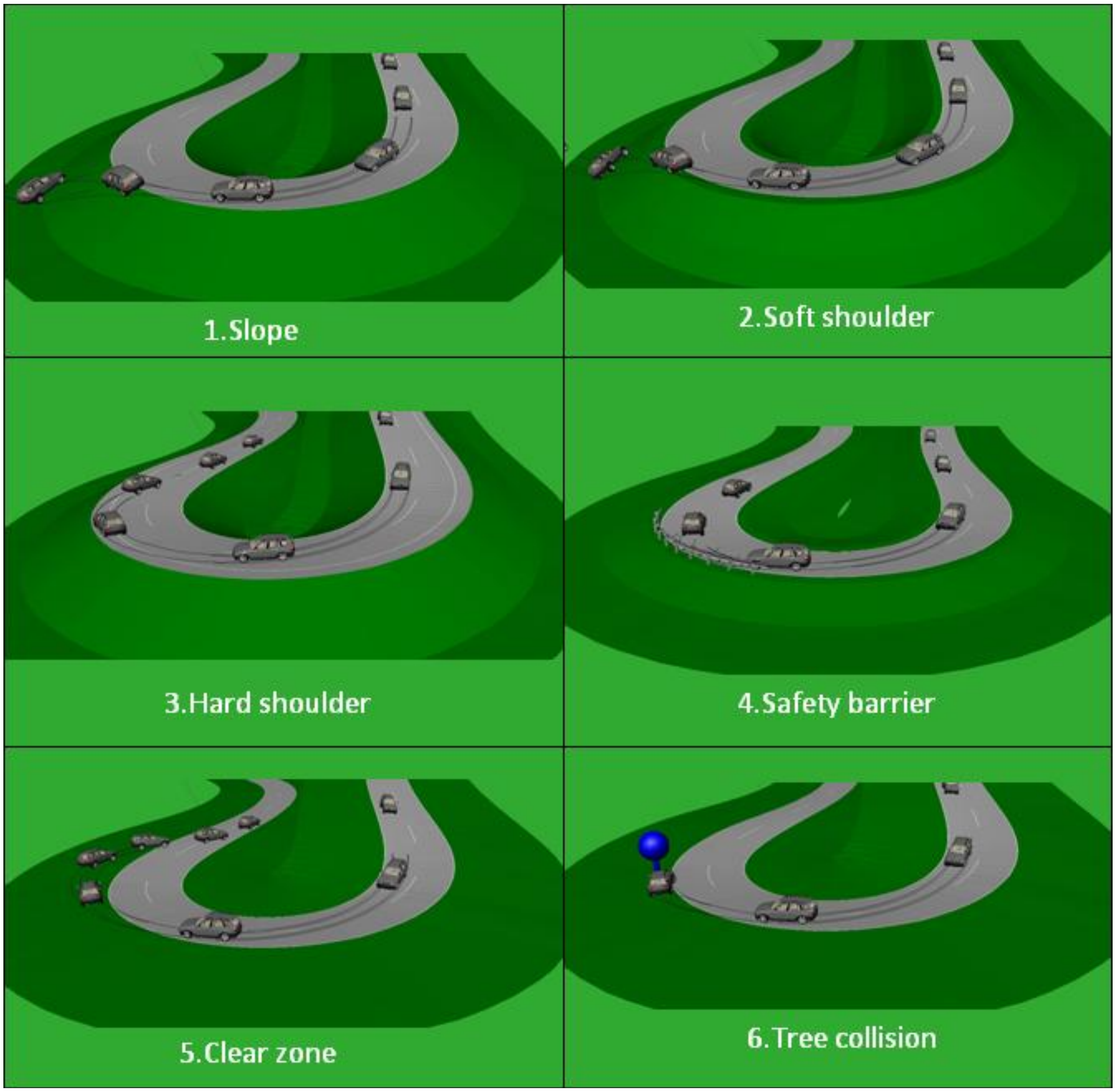

Figure 9: Results of the simulation scenarios

Among these exemplary simulation scenarios, the slope, the soft shoulder and the tree collision resulted in a high risk of fatal injuries to the occupants. This is an indicator that other treatments are necessary at this specific accident spot. Solely with the safety barrier, a slight injury is likely for the driving maneuver simulated.

In this paper, the simulation framework developed is used as a supporting tool to demonstrate the effects of several roadside treatments on safety. Road administrators and road safety inspectors and auditors can benefit by assessing the effects of specific roadside treatments for pre-defined road sections. For the final decision on roadside treatments, it may be necessary to perform an additional inspection at the spot. Other factors such as environmental impacts or cost-benefit ratio have to be included in this decision.

CONCLUSIONS

This paper introduced a novel approach for assessing the effectiveness of roadside safety treatments. A simulation framework has been created, which comprises the modeling of specific road sections as well as simulations of run-off-road accident scenarios with varying roadside treatments such as slope or ditch modifications, shoulder treatments and road restraint systems. Simulations are based on the software PC-Crash and are carried out on accurate replications of real accident black spots in Austria. Three-dimensional road and roadside models of the previously identified accident black spots were created from data of the RoadSTAR system that measures road surface condition as well as roadside objects with laser and/or video equipment. In addition to the road models, the framework includes the definition of vehicle models as well as driver models to carry out specific maneuvers.

The simulation framework was applied to an accident black spot, where three fatal run-off-road accidents occurred. For this spot, six different simulation scenarios with varying roadside treatments were implemented to obtain information about their impact on safety. Simulations of a vehicle running off the road with a pre-defined driving speed were analyzed regarding vehicle dynamics and forces acting on the occupants. Therefore, the head injury criterion (HIC) in combination with the abbreviated injury scale (AIS) was utilized as an assessment method. Simulations of this specific test case resulted in different injury severity for the occupants. In three of the six scenarios (side slope, soft shoulder and tree accident), the run-off-road accident simulation resulted in fatal consequences considering the HIC and AIS. These consequences could be mitigated with the implementation of superior forgiving roadside design. Other scenarios comprised the simulation of run-off-road accidents with hard shoulders as well as wide clear zones. These two treatments could be identified as the most suitable safety measure for this specific spot. Moreover, the effectiveness of a safety barrier to prevent vehicles running off the road was analyzed. Simulations resulted in a slight injury for the occupants.

To verify simulation results for non-fatal accidents, less critical accident locations will be analyzed as next step. Accidents reconstructed by the police provide input data in order to calibrate the simulations. Additional driving scenarios with a probe vehicle equipped with accelerometers in critical situations are planned. This probe vehicle allows a validation of the vehicle model. A global statement about the effectiveness of certain treatments depends on several other factors such as driving speed, trajectory and road alignment, which have to be considered individually for every accident spot. The framework presented in this paper can be used as a tool for supporting road safety inspections (RSI) or road safety audits (RSA) by virtually reconstructing road sections existing or newly planned. The respective roadside can then be modified with appropriate safety treatments, before run-off-road accidents can be simulated. In future, a more detailed acquisition of the roadside is planned with highly sophisticated 3D laser scanning methods. This allows a superior reconstruction of roadsides and improves the validity of the simulation framework.

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